

The drum spring (DS) retractor: a constant and continuous force for canine retraction

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SUMMARY Although much research has been undertaken on the rate of tooth movement, with different hypotheses having been put forward, the concepts of threshold, light, heavy and optimal forces are not still clear.

It has been stressed that an ideal orthodontic spring should have the ability to release a constant force throughout the entire range of its activation, but using traditional techniques applied initial force will decrease, depending on its deactivation due to the tooth movement and the physical properties of the force delivery system. The purpose of this study was to test the clinical use of a new and original spring, the drum spring (DS) retractor (developed in 1992), which applies a constant and continuous force without the need for reactivation, and to compare the effect of a constant and continuous force versus a continuous but diminishing force produced by a traditional pull coil (PC) retractor system on the rate of upper canine retraction.

The clinical sample consisted of 15 patients with upper first premolar extractions. For each patient, the upper right canine was retracted by using a DS retractor applying a constant and continuous force of 50 g; the upper left canine was fitted with a conventional PC applying an initial force of 50 g, diminishing proportionally with the distal movement of the canine. In addition, each group was divided according to the age of each patient: eight patients (three males, five females) between 11.8 and 14.4 years of age (mean 13 ± 1.2 years) represented the adolescent group, and seven patients (three males, four females) between 18.8 and 21.6 years of age (mean 18.2 ± 1.9 years) representing the adult group. The experimental period started 1 week after the extraction of the first premolars. During this period no archwire was used, to avoid friction and force level changes, and the both springs were attached to a 6 mm hook fixed on the canine bracket to reduce tipping. The PC retractor was reactivated every 3 weeks whereas the DS retractor was left untouched over the entire experimental period. The study was continued until one of the two canines was completely retracted. The DS retractor was successful for space closure without any reactivation, and the continuous and constant force provided a more rapid canine movement than the continuous but diminishing force. Canine retraction occurred faster in adolescents than in adults. An entire field of clinical and research applications may be influenced by this new type of spring.

Introduction

Quantity as well as quality of orthodontic forces have been discussed for more than a century. 'Ideal tooth movement', 'limits of biological safety', patient comfort, duration and level of force, and mechanical factors have been investigated by many clinicians and researchers (Schwartz, 1932; Begg, 1956; Burstone *et al.*, 1961; Reitan, 1967; Roberts *et al.*, 1981; Mostafa *et al.*, 1983; Proffit, 1986; Miura *et al.*, 1988).

Tooth movement is primarily a periodontal

membrane phenomenon and is a consequence of alveolar bone remodelling and bone turnover, which is generally thought to be related to biological factors (Mundy, 1987; Davidovitch *et al.*, 1992; Roberts *et al.*, 1992), nutrition (Migrett *et al.*, 1981; Collins and Sinclair, 1988), orthodontic force systems (Proffit, 1986; Roberts *et al.*, 1992) and various local (maxilla versus mandible, tooth length and morphology, alveolar bone level) (Burstone, 1986; Roberts *et al.*, 1992) and environmental factors (seasons,

altitude, magnetic fields, etc.) (Stutzmann *et al.*, 1979; Stark and Sinclair, 1987; Darendeliler *et al.*, 1995). Above all, orthodontic force systems have a direct influence on tooth movement and it is generally accepted that the biological safety is closely related to the amount of force applied (Reitan, 1967; Weinstein, 1967), the age of the patient and the cellular turnover of alveolar bone (Stutzmann *et al.*, 1979; King *et al.*, 1992). The basic idea is that because of root surface differences, an ideal force intensity that will move teeth at an optimal rate exists for each type of tooth and that several variables, such as force system, initial tooth displacement, stress, strain and biological changes of the periodontium, should be taken into consideration to obtain optimal tooth movements (Smith and Storey, 1952; Burstone *et al.*, 1961; Tanne *et al.*, 1992). Different hypotheses have been put forward on stress magnitude and the rate of tooth movement, but the concepts of threshold, light, heavy and optimal forces are still not clear (Oppenheim, 1944; Smith and Storey, 1952; Andreasen and Johnson, 1967; Hixon *et al.*, 1969, 1970; Boester and Johnston, 1974; Nikolai, 1975; Quinn and Yoshikawa, 1985; Burstone, 1986).

Experimental studies have stressed the rate of hyalinization as a rate-limiting factor of orthodontic tooth movement. The application of light and continuous forces results in short hyalinization periods followed by direct bone resorption and relatively rapid tooth movement (Reitan, 1985). It is also reported that orthodontic tooth movement is possible without an initial period of overcompression and hyalinization (Rygh *et al.*, 1986). Undoubtedly, it is not the absolute magnitude of the delivered force that is important but, rather, the distributed load or stress in the surrounding periodontal ligament (PDL) and resultant strain (Storey and Smith, 1952; Burstone, 1986; Tanne *et al.*, 1987).

Force constancy and continuity should also be taken into consideration in an optimal orthodontic force system (Burstone, 1986). Every type of force applied initially using traditional techniques will decrease depending on deactivation due to tooth movement and the physical properties of the force delivery system. In other words, conventional force systems fail to deliver

constant forces. Furthermore, this appears to hold true even with the advent of recent materials (Miura *et al.*, 1988; Angolkar *et al.*, 1992).

Burstone *et al.* (1961) stressed that an ideal orthodontic spring should have the ability to release a constant force throughout the entire range of its activation. Proffit (1986) stated that 'only in theory is it possible to produce a perfect spring, one that can deliver the same continuous force day after day, no matter how much or how little the tooth moves in response to that force'.

The purpose of this study was to test the clinical use of a new and original spring, the drum spring (DS) retractor, developed in 1992 (Darendeliler, 1993), which applies a constant and continuous force without the need for reactivation and to compare the effect of a constant and continuous force versus a continuous but diminishing force produced by a traditional pull coil (PC) retractor system on the rate of tooth movement.

Subjects and method

The clinical sample consisted of 15 patients with upper first premolar extractions. For each patient, the upper right canine was retracted by using the DS retractor applying a constant and continuous force of 50 g (DS group) (Fig. 1a); the upper left canine was fitted with a conventional PC applying an initial force of 50 g, diminishing proportionally with the distal movement of the canine (PC group) (Fig. 1b). In addition, each group was divided according to the age of each patient: eight patients (three males, five females) between 11.8 and 14.4 years of age (mean 13 ± 1.2 years) represented the adolescent group, DS₁ and PC₁, and seven patients (three males, four females) between 18.8 and 21.6 years of age (mean 18.2 ± 1.9 years) representing the adult group, DS₂ and PC₂. The experimental period started 1 week after the extraction of the first premolars; great care was taken to avoid surgical trauma to the vestibular or palatal cortical bony plate.

Both springs were attached to a 6 mm hook fixed on the canine bracket to reduce tipping. During the experimental period, no archwire was

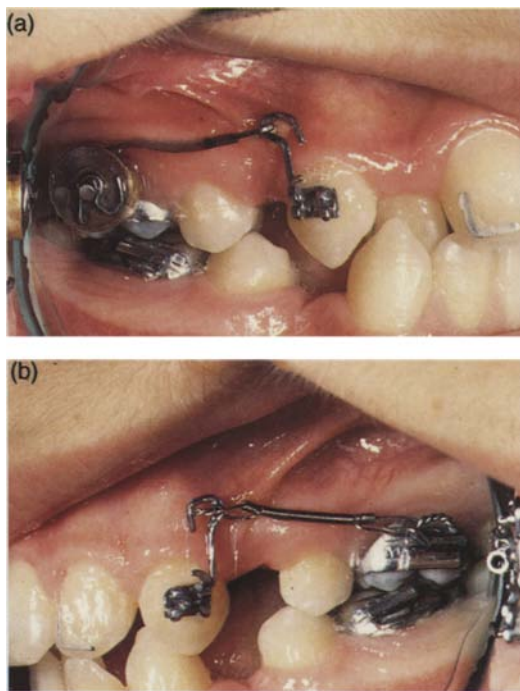


Figure 1 Intraoral views of (a) the drum spring (DS) retractor applying 50 g of constant and continuous force, and (b) the pull coil (PC) retractor applying 50 g of initial force diminishing proportionally to the distal movement of the canine. Note the metallic markers on the incisors.

used to avoid friction and force level changes, and maximum attention was paid to select patients without any contact between the upper canines and the lower arch (Fig. 1). The PC retractor was reactivated every 3 weeks, whereas the DS retractor was left untouched over the entire experimental period. The study was continued until one of the two canines was completely retracted.

Lateral and basilar cephalometric X-ray films and photographs were taken immediately prior to and after completion of the movement; measurements of periodontal pockets of right and left canines were performed before and after the experimental period with a graduated periodontal probe. Clinically, the extraction spaces of the DS and PC sides were measured every 3 weeks with the aid of a dial caliper gauge accurate to the nearest 0.1 mm. For a more accurate evaluation of rotational and tipping movements of pre- and post-treatment cephalo-

metric films, 'L' shaped orthodontic rectangular stainless steel wires (0.0018" \times 0.025" and 0.014") were bonded on the maxillary incisors (Fig. 1) and 1 mm diameter wires were soldered on the molar bands. Sagittal, vertical and horizontal dental movements were measured on the basilar and lateral cephalometric films (Fig. 2a-c). The changes on the lateral cephalometric films were evaluated according to Björk's (1964) superimposition (Fig. 2c).

The rate of the right and left canine movement was compared in 15 patients. In a second evaluation, the influence of age on canine movement was observed by comparing the results of the adolescents (DS₁ and PC₁) and the adults (DS₂ and PC₂) on the DS and PC sides separately. Differences between treatment effects of the two types of retraction mechanisms and age groups were evaluated statistically using Student's *t*-test for paired and unpaired samples, respectively. A significance level of $P < 0.05$ was established. According to the error analysis, an average error of 5 per cent was revealed.

The cumulative amount of stress, defined as the amount of force per unit of root surface received by the right and left canine, was calculated from the clinical data where the root surface for the canines was taken 2.5 cm² (Chateau, 1975) to evaluate if any correlation existed between the amount of stress applied and canine movement. This amount was calculated for each patient at 3 weekly intervals and regression analysis was used with the corresponding canine movements for DS and PC sides.

Appliance design

The DS retractor is designed for intraoral use to produce a force which remains constant without the need for reactivation (Figs. 3 and 4) and consists of four parts (Figs. 5 and 6): (1) a constant force spring (CFS) (Vulcan Spring & MFG. Co., PA) with a hook especially designed and fabricated to apply 50 g of constant and continuous force (Fig. 5b,c,f); (2) a drum (Fig. 5a); (3) a spring box (SB) (Fig. 5d,e,f); and (4) a central pin soldered to the molar band (CW) (Fig. 6).

When assembled and mounted on the molar band, the DS retractor is activated by pulling the

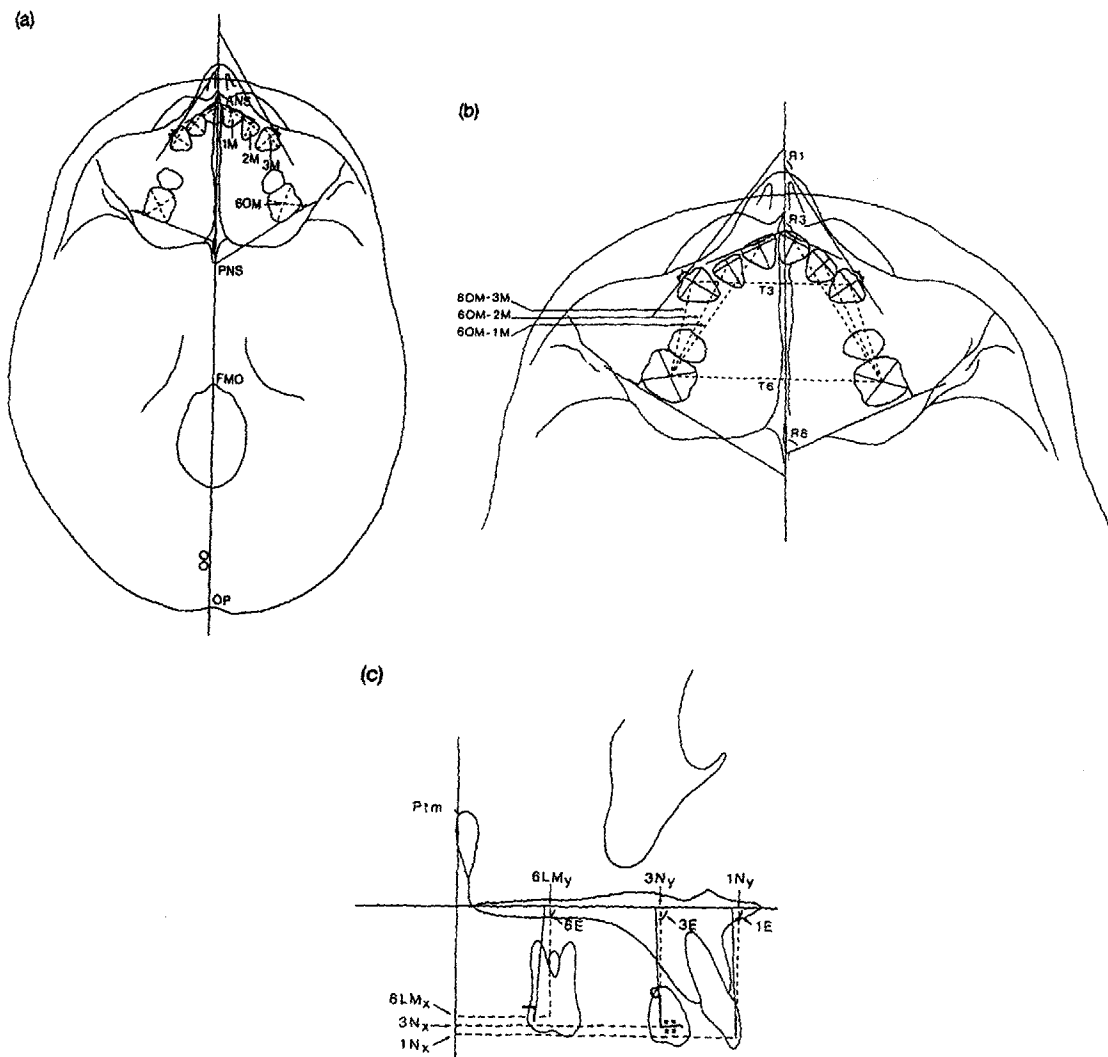


Figure 2 Cephalometric points and measurements on (a,b) the basilar and (c) the lateral cephalometric films. (a) Occlusal central tooth points (1M, 2M, 3M, 6OM); transversal tooth axes of the central incisors, canines and molars; (b) linear measurements on the sagittal (distances between upper first molars and upper anterior teeth) and transversal (distances between upper left and right molars) planes and angular measurements [central incisor (R1), canine (R2), and molar (R3) axes to the mid-sagittal plane]; and (c) sagittal (6LMx, 3Nx, 1Nx) and vertical (6LMy, 3Ny, 1Ny) linear and angular (6E, 3E, 1E) measurements on the lateral local superimposition.

end of the spring (Figs 1a and 7a,b). The amount of activation does not influence the amount of force applied, which was 50 g in this study (Fig. 8a,b,c).

The PC retractor system comprises an 8 mm long stainless steel PC spring ($0.006'' \times 0.020''$) (Hi-T Coil Spring; 341-110, Unitek Co., CA) producing an initial force of 50 g, decreasing according to the equation $y = 11.65 + 20.28x$.

This system was reactivated every third week to its initial length (Figs 9 and 10).

Results

The retraction systems used in this study were well tolerated by the patients during the experimental period (mean 13.26 ± 4.45 weeks). Both the DS and PC systems proved effective in



Figure 3 DS retractor on the typodont.

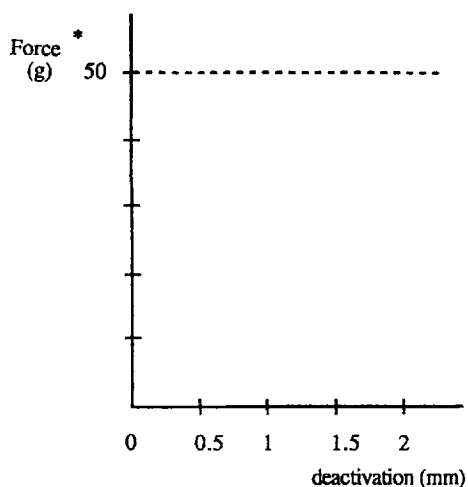


Figure 4 Force produced by the DS retractor. ± 5 g according to Vulcan Spring & MFG Co., PA, USA.

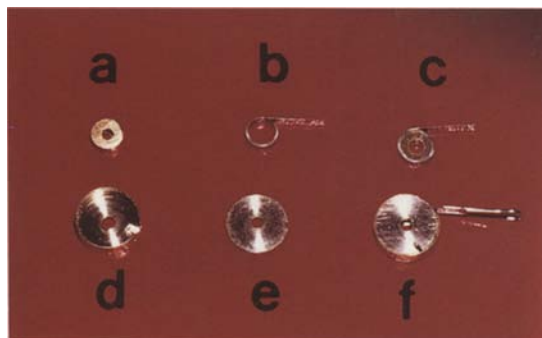


Figure 5 The parts of the DS retractor: (a) drum, (b) constant force spring (CFS), (c) CFS mounted on the drum, (d) spring box (SB), (e) spring cover and (f) DS retractor.

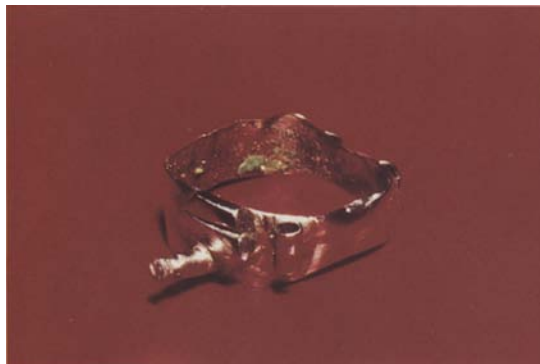


Figure 6 Upper right molar band with central pin soldered on its vestibular face.

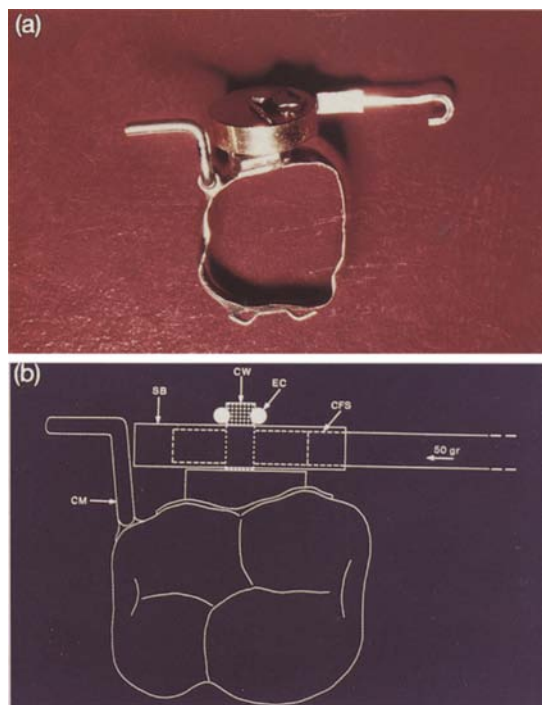


Figure 7 (a) Occlusal and (b) schematic views of the upper right molar band with the DS retractor. CFS, constant force spring; SB, spring box; CN, central pin; CM, metallic marker; EC, E clips.

distalizing canines (Fig. 11); overall results are shown in Tables 1–6.

Extraction space closure

From the third week onward, the clinical space closure measured every third week showed

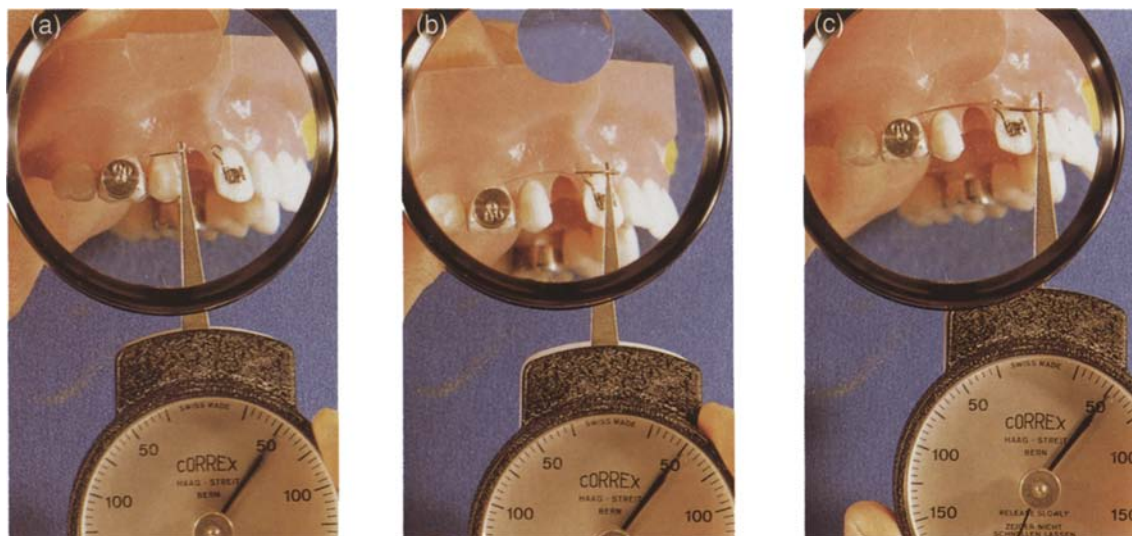


Figure 8 DS retractor activated (a) 7 mm, (b) 15 mm and (c) 18 mm on the typodont. The amount of activation does not change the amount of force delivered by the DS retractor.

higher values for the DS retractor (Fig. 12) and reached the $P = 0.000$ level of significance by week 18 (Table 4).

Amount of canine retraction

Canine retraction measured on the lateral cephalometric radiographs was much larger on the DS side than on the PC side ($P < 0.001$) in all 15 patients. Furthermore, the amount of retraction on the DS side was also greater in adolescents ($DS_1/PC_1 = P < 0.001$) and in adults ($DS_2/PC_2 = P < 0.05$) (Tables 1–3: distance 3Nx).

Monthly canine retraction rate

According to the radiological results, the mean monthly canine distalization rate was greater on the DS side for the overall sample ($P < 0.001$) as well as for both individual sub-groups ($P < 0.05$) (Tables 5 and 6). The difference was marked for the adolescent group, with 1.975 ± 0.615 mm for the DS side and 1.515 ± 0.555 mm for the PC side (Table 6).

Even though both systems demonstrated significant anchorage loss, no difference was observed between the DS and PC sides (Table 1, distance 6LMx).

Despite significant changes in all other parameters (i.e. mesial tipping or rotation of the

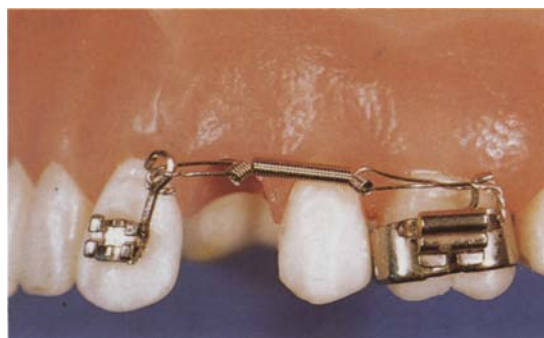


Figure 9 PC retractor on the typodont.

molars, or distal tipping or rotation of canines), no differences were observed between the DS and PC sides during the experimental period (Table 1, angles R6, R3, 6E, 3E).

The amount of molar mesialization was similar on both sides, but the ratio of mesialization of posterior teeth to overall extraction space closure was found to be 24.6 per cent for the DS side and 34 per cent for the PC side (Table 5).

Canine tipping per millimetre of canine distal movement was significantly less accentuated ($P < 0.05$) on the DS side (1.182 ± 1.416 degrees) than on the PC side (2.314 ± 2.241 degrees)

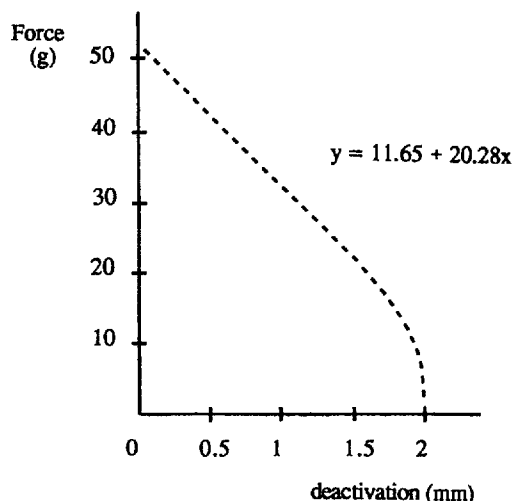


Figure 10 Force decrease related to the deactivation of the PC retractor.

(Table 7). When the PC sides of the adolescent and adult groups were compared, the amount of rotation produced by 1 mm of canine movement was predominant in the adult group. On the other hand, the molar tipping produced by 1 mm of molar movement was significantly more pronounced in the adolescent group than in the adult group (Table 8, R3/3Nx, 6E/6LMx).

A correlation ($r = 0.76$) was found between the total amount of stress applied and the space closure (Fig. 13).

Measurements of the periodontal pockets of the canines prior to treatment and immediately after showed an increase ($P < 0.05$) of the pocket depth for the right canines (DS side) (Table 1, 3Pp).

No significant sagittal and vertical skeletal changes were found between pre- and post-treatment cephalometric evaluation.

Discussion

The feasibility of a new and original canine retraction spring which applies constant and continuous force was demonstrated in this clinical study. The DS retractor was more effective in all 15 patients than the PC system. The monthly mean canine distalization rates for the two springs were 1.648 ± 0.576 and $1.214 \pm$

0.576 mm ($P < 0.001$) respectively (Table 5), with large differences between the adolescent and adult groups (Table 6). The highest rate was obtained in a 14 year old girl, and was 2.755 mm per month on the DS and 2.00 mm per month on the PC side. Since the 50 g of force chosen in this study seems to be within biological limits for the upper canine tooth and that the optimal tooth movement rate of 3 mm per month mentioned by Roberts *et al.* (1981) is not attained, 50 g of force is probably below the optimal force level and biological potential for upper permanent canines.

Although the differences observed between the two age groups could be easily explained by some morphological and developmental specifics (i.e. bone density, cellular turnover, periodontal tissue response, etc.), very few studies dealing with canine retraction mechanisms have stressed the possible causative factors involved in such an observation (Björk, 1964; Dyer *et al.*, 1991; Roberts *et al.*, 1992). Despite reports of various amounts of tooth movement and retraction rates with a large range of force utilization (Paulson *et al.*, 1970; Sleichter, 1971; Ziegler and Ingervall, 1989), it is interesting that the rate of canine movement observed in our sample was greater with the DS irrespective of age factors and bearing in mind the fact that there could be no dilution of forces by friction.

Considering that the 'blood capillary pressure', according to Schwartz (1932), is 20–26 g/cm² and that the mean surface area of the canine root is 2.5 cm² (Chateau, 1975), 50 g of force was chosen in the study to be within biological limits. This produced an almost linear path of canine movement for both retraction systems (Fig. 12). According to the results obtained, it is obvious that constant and continuous forces delivered by the DS were 'more effective' than diminishing continuous forces delivered by the PC. However, it cannot be excluded that the biological conditions may vary under different force levels, thereby producing different results.

It is generally accepted that orthodontic tooth movement within the limits of biological safety is closely related to the force applied. For each type of tooth there is an optimal force level leading

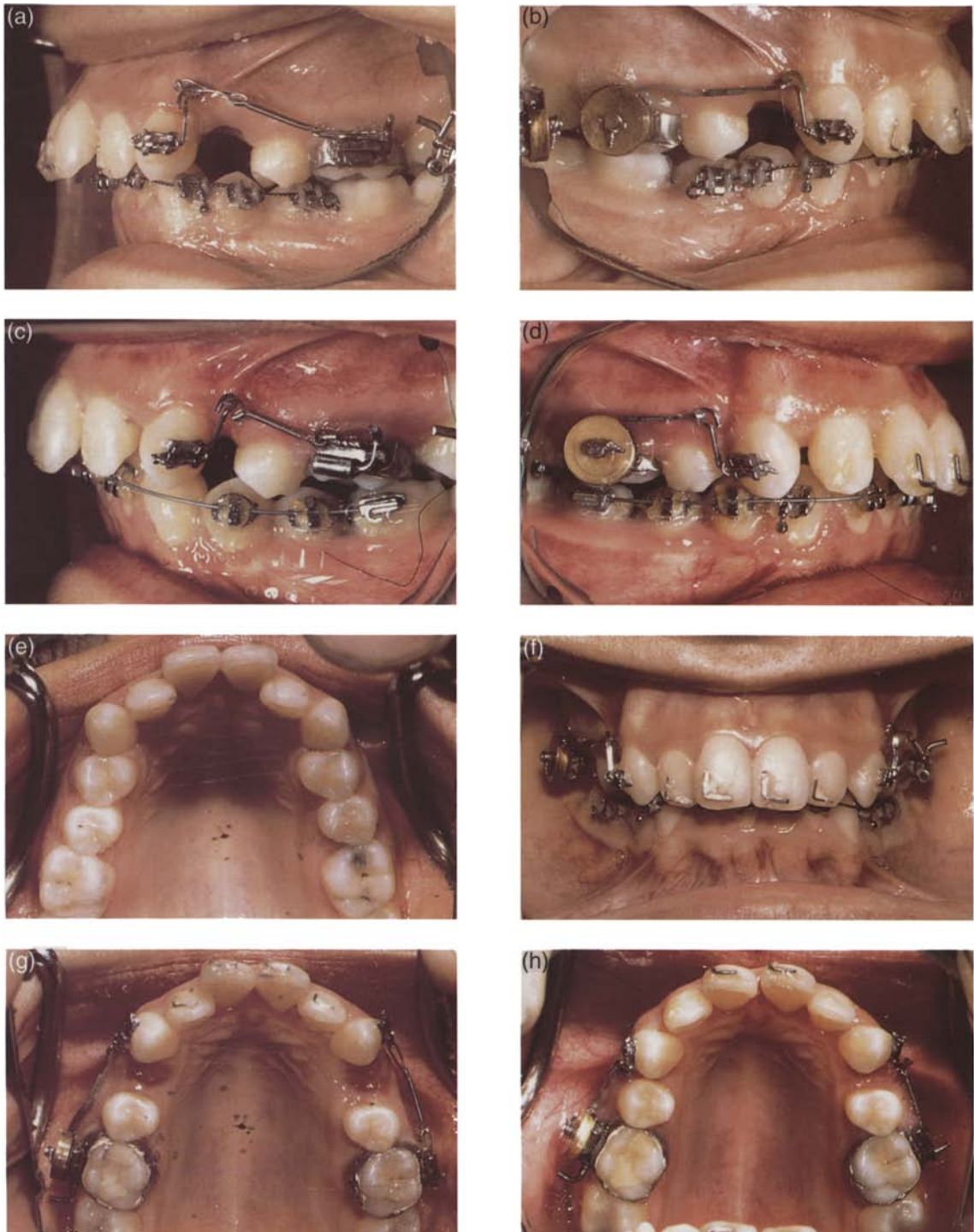


Figure 11 Intraoral view of an adult case: (a,b,c,f,g) before and (d,e,h) after the experimental period.

Table 1 Statistical values of the cephalometric measurements of DS and PC sides in all patients ($n=15$); d1 and d2: mean values of the dental effects on DS and PC sides; d1 – d2: mean value of the difference between the effects of the DS and PC sides

Basilar	Drum spring (DC)		Pull coil (PC)		DS/PC	
	d1 \pm SD	P	d2 \pm SD	P	d1 – d2 \pm SD	P
6OM-3M	5.320 \pm 1.897	0.0000***	3.813 \pm 2.176	0.0000***	1.507 \pm 1.624	0.0029**
6OM-2M	3.020 \pm 1.717	0.0000***	1.900 \pm 2.385	0.0081**	1.120 \pm 1.826	0.0320*
6OM-1M	2.653 \pm 1.705	0.0000***	1.367 \pm 2.225	0.0320*	1.287 \pm 1.816	0.0160*
R6	12.867 \pm 8.883	0.0001***	13.767 \pm 10.647	0.0002***	-0.900 \pm 10.792	0.7500
R3	-25.267 \pm 10.119	0.0000***	-27.800 \pm 13.946	0.0000***	2.533 \pm 16.772	0.5700
R1	-0.933 \pm 4.358	0.4200	-0.600 \pm 5.877	0.700	-0.333 \pm 3.299	0.7000
	d1 \pm SD	P				
T6	1.293 \pm 2.022	0.0270*				
T3	-0.720 \pm 1.145	0.0290*				
ASA	-1.080 \pm 1.026	0.0011**				
Lateral	d1 \pm SD		d2 \pm SD		d1 – d2 \pm SD	
	d1 \pm SD	P	d2 \pm SD	P	d1 – d2 \pm SD	P
6E	5.600 \pm 5.755	0.0021**	5.667 \pm 5.499	0.0054**	0.933 \pm 5.603	0.5300
6LMx	-1.973 \pm 1.805	0.0008***	-1.733 \pm 1.744	0.0018**	-0.240 \pm 0.897	0.3200
6LMy	0.427 \pm 0.907	0.0900	0.227 \pm 1.269	0.5000	0.200 \pm 1.753	0.6700
3E	-4.467 \pm 5.125	0.0045**	-4.533 \pm 8.299	0.0530	0.067 \pm 4.625	0.0960
3Nx	5.307 \pm 2.131	0.0000***	4.040 \pm 2.433	0.0000***	1.267 \pm 1.126	0.0007***
3Ny	-0.653 \pm 1.036	0.0280*	-0.947 \pm 1.528	0.0310*	0.293 \pm 1.895	0.5600
1E	-1.000 \pm 3.396	0.2700	-0.800 \pm 3.358	0.3700	-0.200 \pm 2.145	0.7200
1Nx	0.353 \pm 0.924	0.1600	0.400 \pm 1.045	0.1600	-0.047 \pm 0.549	0.7500
1Ny	-0.027 \pm 1.767	0.9500	-0.287 \pm 1.783	0.5400	0.260 \pm 0.724	0.1900
3Pp	-0.025 \pm 0.375	0.0160*	-0.066 \pm 0.383	0.5100	-0.183 \pm 0.383	0.0850

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

to a maximum rate of tooth movement with minimum tissue hazard (Storey and Smith, 1952; Reitan, 1967). An optimal orthodontic force system is defined as a force system which produces maximum biological response with minimum tissue damage, resulting in the most rapid tooth movement with little or no clinical discomfort (Smith and Storey, 1952). Researchers have often considered certain force levels to be optimal without taking into account the important changes in force intensity during tooth movement. Traditional appliances produce continuous but diminishing forces where only the level and not the duration of force has an intermittent character. Light forces of intermittent duration are considered to be more favourable than continuous forces because less

strain is applied on the tissues, which therefore improves their chances for repair and response to mechanical stimulus (Oppenheim, 1944; Norton, 1985; Yen *et al.*, 1992). On the other hand, the 'ideal force' has already been defined as being constant and continuous (Burstone *et al.*, 1961; Proffit, 1986), with continuous forces being the most efficient in changing the position of the tooth (Roberts *et al.*, 1992) even if their biological parameters are still unknown (Burstone, 1986). Without dismissing their obvious clinical benefits, the relatively constant force delivery of Ni-Ti coil springs still shows a decrease of approximately 25 g with the first millimeter of tooth movement (Miura *et al.*, 1988; Angolkar *et al.*, 1992). However, for research on the rate of tooth movement, the

Table 2 Statistical values of the cephalometric measurements of DS and PC sides in the adolescent group ($n = 8$); d1 and d2: mean values of the dental effects on DS and PC sides; d1 – d2: mean value of the difference between the effects of the DS and PC sides.

Basilar	Drum spring (DS _I)		Pull coil (PC _I)		DS _I /PC _I	
	d1 ± SD	P	d2 ± SD	P	d1 – d2 ± SD	P
6 OM-3M	6.087 ± 1.817	0.0000***	4.250 ± 2.785	0.0036**	1.838 ± 1.627	0.0150*
6OM-2M	3.500 ± 1.648	0.0006***	2.650 ± 2.658	0.0260*	0.850 ± 1.407	0.1300
6OM-1M	3.100 ± 1.431	0.0005***	2.125 ± 2.055	0.0220*	0.975 ± 1.199	0.0550
R6	15.500 ± 6.892	0.0004***	14.938 ± 10.051	0.0042**	0.563 ± 9.923	0.8800
R3	-25.125 ± 12.091	0.0006***	-25.313 ± 17.688	0.0050**	0.187 ± 22.003	0.9800
R1	0.125 ± 1.706	0.8400	1.000 ± 3.024	0.3800	-0.875 ± 3.613	0.5200
	d1 ± SD	P				
T6	1.775 ± 0.729	0.0002***				
T3	-0.638 ± 1.031	0.1200				
ASA	-1.213 ± 0.677	0.0016**				
Lateral	d1 ± SD		d2 ± SD		d1 – d2 ± SD	
	d1 ± SD	P	d2 ± SD	P	d1 – d2 ± SD	P
6E	5.687 ± 5.438	0.0210*	5.667 ± 5.499	0.0054**	0.933 ± 5.603	0.5300
6LMx	-1.862 ± 1.214	0.0035**	-1.733 ± 1.744	0.0018**	-0.240 ± 0.897	0.3200
6LM _y	0.225 ± 0.965	0.5300	0.227 ± 1.269	0.5000	0.200 ± 1.753	0.6700
3E	-7.500 ± 4.528	0.0024**	-4.533 ± 8.299	0.530	0.067 ± 4.625	0.0960
3Nx	5.650 ± 2.563	0.0004***	4.040 ± 2.433	0.0000***	1.267 ± 1.126	0.0007***
3Ny	-0.475 ± 0.963	0.2100	-0.947 ± 1.528	0.0310*	0.293 ± 1.895	0.5600
1E	-2.812 ± 2.645	0.0200*	-0.800 ± 3.358	0.3700	-0.200 ± 2.145	0.7200
1Nx	0.500 ± 0.714	0.0890	0.400 ± 1.045	0.1600	-0.047 ± 0.549	0.7500
1Ny	0.750 ± 1.742	0.2600	-0.287 ± 1.783	0.5400	0.260 ± 0.724	0.1900
3Pp	-0.281 ± 0.388	0.0800	-0.187 ± 0.395	0.2200	-0.94 ± 0.229	0.2900

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

constancy of the force level becomes an important factor.

Several theories exist regarding the bone adaptive response to external mechanical loads (Frost, 1983,1987; Carter *et al.*, 1989; Hart and Davy, 1989). Studies undertaken on tooth movement and bone adaptive response stress the importance of:

1. The major factor that truly affects the movement of teeth is not really the force magnitude but rather the distribution of stress generated by the appliance in the surrounding peridontium (Quinn and Yoshikawa, 1985; Tanne *et al.*, 1987; 1989; Rygh, 1992). Taking into consideration the tooth morphology, tooth length and periodontal ligament–bone

morphology and using the finite element method, it was reported that different distributions of force and creations of stress are obtained using similar or different force levels (Burstone, 1986). Local stress and strains generated in the tissues by force application influence the duration and intensity of cellular responses related to the cellular reactions, to differentiate osteoclast and osteoblast for bone remodelling (Tanne *et al.*, 1987, 1992).

2. There exists a 'saturation limit' where the adaptive capability of the bone is at a maximum (Frost, 1990). This phenomenon very probably reflects the obtention of the maximum tooth movement rate without any pathological side effects.

Table 3 Statistical values of the cephalometric measurements of PC sides in the adult group ($n = 7$); d1 and d2: mean values of the dental effects on DS and PC sides; d1 – d2: mean value of the difference between the effects of the DS and PC sides.

Basilar	Drum spring (DC ₂)		Pull coil (PC ₂)		DC ₂ /PS ₂	
	d1 ± SD	P	d2 ± SD	P	d1 – d2 ± SD	P
6OM-3M	4.443 ± 1.691	0.0004***	3.314 ± 1.208	0.0003***	1.129 ± 1.658	0.1200
6OM-2M	2.471 ± 1.747	0.0096**	1.043 ± 1.849	0.1900	1.429 ± 2.295	0.1600
6OM-1M	2.143 ± 1.956	0.0270*	0.525 ± 2.232	0.5800	1.643 ± 2.396	0.1200
R6	9.857 ± 10.435	0.0470*	12.429 ± 11.946	0.0330*	-2.571 ± 12.279	0.6000
R3	-25.429 ± 8.264	0.0002***	-30.643 ± 8.444	0.0001***	5.214 ± 8.708	0.1600
R1	-2.143 ± 6.142	0.3900	-2.429 ± 7.913	0.4500	-0.286 ± 3.053	0.8100
	d ± SD	P				
T6	0.743 ± 2.873	0.5200				
T3	-0.814 ± 1.341	0.1600				
ASA	-0.929 ± 1.367	0.1200				
Lateral	d1 ± SD		d2 ± SD		d1 – d2 ± SD	
	d1 ± SD	P	d2 ± SD	P	d1 – d2 ± SD	P
6E	5.500 ± 6.538	0.0680	3.357 ± 2.076	0.0240*	-3.143 ± 6.926	0.2800
6LMx	-2.100 ± 2.418	0.0610	-2.129 ± 1.762	0.0190*	0.029 ± 0.660	0.9100
6LMy	0.657 ± 0.846	0.0860	0.200 ± 0.827	0.5500	0.457 ± 0.632	0.1000
3E	-1.000 ± 3.329	0.4600	-0.357 ± 8.664	0.9200	0.643 ± 5.984	0.7900
3Nx	4.914 ± 1.611	0.0002***	3.400 ± 2.091	0.0051**	1.514 ± 1.548	0.0410*
3Ny	0.857 ± 1.153	0.0970	0.657 ± 1.702	0.3300	0.200 ± 2.586	0.8400
1E	1.071 ± 3.061	0.3900	-0.143 ± 3.532	0.9200	1.214 ± 1.410	0.0630
1Nx	0.186 ± 0.154	0.6900	0.129 ± 1.191	0.7800	0.057 ± 0.526	0.7800
1Ny	0.914 ± 1.223	0.1400	-1.129 ± 1.981	0.1800	0.214 ± 0.901	0.5500
3Pp	0.214 ± 0.336	0.1400	0.071 ± 0.345	0.6000	-0.286 ± 0.509	0.1900

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

In this study the amount of stress received by the tooth and the surrounding periodontium during the experimental period was found to be proportional to the amount of tooth movement ($r = 0.76$). Similarly, Goldstein (1992) reported significant time-dependent morphological correlations between changes in mechanical stresses and subsequent morphological alterations. In the present study the periodontal structures received equal amounts of stress with the first activation, but subsequently the initial stress decreased on the PC side due to the deactivation of the coil spring. Therefore the cumulative stress produced by the PC is significantly less than that produced by the DS. This may contribute to the difference in rate of tooth movements registered. Thus the amount of

stress becomes important and a 'stress related tooth movement' concept can be supported.

An appliance system delivering relatively continuous stress was suggested by Quinn and Yoshikawa (1985) to minimize anchorage loss. In the present study, anchorage loss expressed by mesial movement of the first molars was surprisingly high on both sides and the difference between the DS and PC sides was not significant (Table 1, 6MLx). This observation confirms the findings of Boester and Johnston (1974), who suggested that anchorage loss was unrelated to the level of force. Reitan (1985) also reported that even with 30 g of force molars would drift mesially. Thus the 'differential forces' theory is once more questioned.

In most experiments, the real amount of force

Table 4 Mean values of the clinical space closure measurements taken every 3 weeks on the DS and PC sides and the mean difference between DS and PC sides.

Week	<i>n</i>	Drum spring (DS), <i>x</i> ± SD	Pull coil (PC), <i>x</i> ± SD	DS/PC, <i>x</i> ± SD	<i>P</i>
3	15	1.200 ± 0.739	0.773 ± 0.561	0.427 ± 0.566	0.0110*
6	15	2.340 ± 1.078	1.693 ± 0.788	0.647 ± 0.886	0.0130*
9	13	3.600 ± 1.460	2.830 ± 1.375	0.785 ± 1.003	0.0150*
12	10	4.940 ± 1.346	3.940 ± 1.559	1.000 ± 0.811	0.0037**
15	7	5.650 ± 0.950	4.428 ± 1.542	1.229 ± 0.984	0.0160*
18	3	6.030 ± 1.115	4.666 ± 1.327	2.831 ± 1.376	0.0000***

P* < 0.05; *P* < 0.01; ****P* < 0.001.

Table 5 The percentage of the canine (3) and molar (6) movements versus canine and molar total (3 + 6) movement (%) and mean values of the canine (3) and canine and molar total (3 + 6) movement per month (mm/month) measured on the lateral cephalometric radiographs on the DS and PC sides (*n* = 15).

	Drum spring (DS), <i>x</i> ± SD	Pull coil (PC), <i>x</i> ± SD	DS/PC, <i>d</i> ± SD	<i>P</i>
3/3 + 6 (%)	73.600 ± 18.474	66.000 ± 22.251	7.600 ± 12.574	0.0350*
6/3 + 6 (%)	26.400 ± 18.474	34.000 ± 22.251	-7.600 ± 12.574	0.0350*
3 (mm/month)	1.648 ± 0.576	1.214 ± 0.576	0.433 ± 0.348	0.0003***
3 + 6 (mm/month)	1.784 ± 0.494	1.283 ± 0.456	0.500 ± 0.362	0.0001***

Table 6 Mean values of the canine (3) and canine and molar (3 + 6) movement per month (mm/month) measured on the lateral cephalometric radiographs on the DS and PC sides in adolescent (*n* = 8) and adult (*n* = 7) groups.

	Drum spring (DS)			Pull coil (PC)		
	Adolescent, <i>x</i> ± SD	Adult, <i>x</i> ± SD	<i>P</i>	Adolescent, <i>x</i> ± SD	Adult, <i>x</i> ± SD	<i>P</i>
3 mm/month	1.975 ± 0.615	1.275 ± 0.170	0.0120*	1.515 ± 0.555	0.870 ± 0.394	0.024*
3 + 6 mm/month	2.110 ± 0.457	1.414 ± 0.146	0.0020**	1.502 ± 0.510	1.034 ± 0.212	0.0420*

P* < 0.05; *P* < 0.01; ****P* < 0.001.

applied is difficult or impossible to determine because of friction due to archwire-slot dimension, degree of slot angulation, insufficiently controlled reactivation and wire factors, and even the tightness of the ligature tie (Sonis *et al.*, 1986; Adams *et al.*, 1987). More importantly, the uncontrolled type of tooth movement as well as large measurement errors in the rate of tooth

movement by the investigators in some studies made their findings difficult to evaluate (Quinn and Yoshikawa, 1985). In this study, as no archwire was used, the force level transferred to the canine tooth could be more precisely analysed. Thus, uncontrolled rotations due to lack of archwire guidance were foreseen. It has already been shown that the moment-force ratio

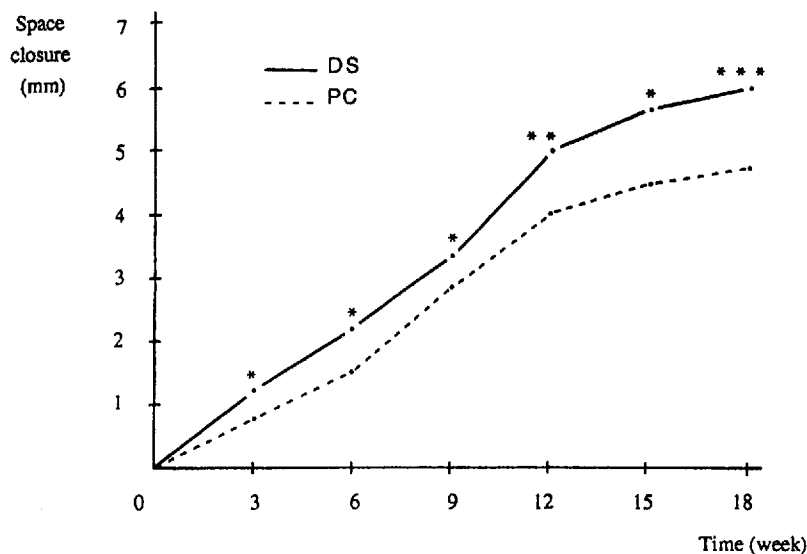


Figure 12 Diagram showing the mean values of the clinical space closure (mm) on the DS and PC retractor sides.

Table 7 Mean canine and molar tipping and canine and molar rotation per mm of canine and molar movement in all patients ($n = 15$).

	Drum spring (DS), $\bar{x} \pm \text{SD}$	Pull coil (PC), $\bar{x} \pm \text{SD}$	DS/PC, $\bar{x} \pm \text{SD}$	<i>P</i>
3E/3Nx	1.182 ± 1.416	2.314 ± 2.241	-1.049 ± 1.359	0.0100**
R3/3Nx	5.691 ± 2.798	8.463 ± 5.137	-2.765 ± 4.664	0.0380*
6E/6LMx	5.652 ± 5.361	8.383 ± 14.134	-2.740 ± 13.270	0.4370
6R/6LMx	14.906 ± 15.523	15.052 ± 16.807	-0.146 ± 18.818	0.9760

* $P < 0.05$; ** $P < 0.01$.

for the canine is between 4/1 and 7/1 when the force is applied to the bracket (Gjessing, 1985; Ziegler and Ingervall, 1989). With both the DS and PC systems, canine disto-buccal rotations (Table 1, R3) and molar mesio-buccal rotations (Table 1, R6) were rather pronounced ($P < 0.001$), but no statistically significant difference was found between the two groups. It has already been reported that the force level needed for tipping and rotational movements is much less than for translation movements (Proffit, 1986). Less tipping per millimetre of canine movement on the DS side than on the PC side ($P < 0.01$) shows that a constant force application seems to produce more bodily movement than a

continuous and diminishing force: 1.182 ± 1.416 and 2.314 ± 2.241 degrees, respectively (Table 7). Although no archwire was used in this study, these values are quite low compared with other clinical studies (Huffman and Way, 1983; Ziegler and Ingervall, 1989), which have reported tipping of 0.6–1.5 degrees with sliding mechanics and 0.8 degrees with non-sliding techniques. Moreover, the force was applied 6 mm apically to the slot of the canine to be near the centre of resistance while avoiding soft tissue damage above the canines. Furthermore, when the two age groups were compared, the rotation of the canine was significantly greater ($P < 0.05$) in the adult group on the PC side (Table 8, R3/3Nx). This difference

Table 8 Mean canine and molar tipping and canine and molar rotation per mm of canine and molar movement in adolescent ($n = 8$) and adult ($n = 7$) groups.

	Drum spring (DS)			Pull coil (PC)		
	Adolescent, $x \pm SD$	Adult, $x \pm SD$	<i>P</i>	Adolescent, $x \pm SD$	Adult, $x \pm SD$	<i>P</i>
3E/3Nx	1.745 \pm 1.781	0.539 \pm 0.265	0.0826	2.412 \pm 2.826	2.024 \pm 1.520	0.6434
R3/3Nx	5.536 \pm 3.206	5.872 \pm 2.489	1.0000	5.745 \pm 2.808	11.569 \pm 5.592	0.0491*
6E/6LMx	7.065 \pm 5.761	4.038 \pm 4.758	0.2900	14.350 \pm 17.634	1.587 \pm 1.380	0.0100**
R6/6Mx	15.989 \pm 15.446	13.668 \pm 16.749	0.5628	18.049 \pm 21.306	11.631 \pm 10.193	0.6430

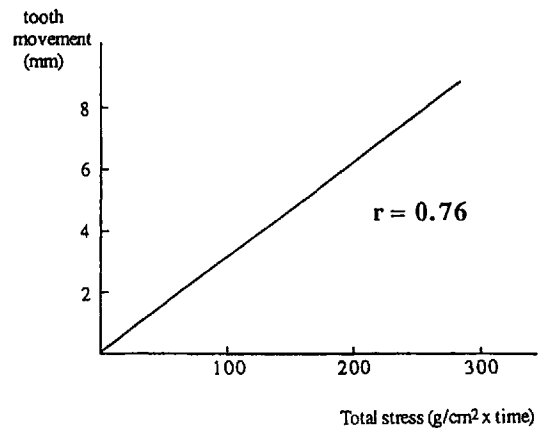
* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

might well be explained by the fact that small magnitude forces produce translation movements rather than rotations in adolescents.

On the basilar radiographs, the measurement of the anterior space for the four incisors showed a significant increase ($P < 0.01$) in all patients and especially those in the adolescent group (Tables 1 and 2, ASA). This movement might be explained by transeptal ligament stretching due to canine distalization and also by distal migration of the central and lateral incisors into the created place.

Periodontal pockets became significantly deeper ($P < 0.05$) on the DS side, which may be due to the lack of adaptation of the periodontal tissues to the amount of movement and tipping (Table 1, 3Pp).

Using traditional appliances, the force delivery systems have to be reactivated or changed by the orthodontist or the patient in order to maintain force delivery. This makes patient cooperation more demanding and chairtime longer, and may fail to provide optimal tooth movement, thereby influencing treatment length. The development of the DS will enable future research on the 'ideal or optimal force' allowing 'ideal or optimal tooth movement'. In addition, DS retractors may be an alternative for canine and anterior segment distalization with the advantage of a constant force without the need for reactivation. An entire field of clinical applications may be influenced by this new type of spring.

**Figure 13** Diagram showing the correlation ($r = 0.76$) between the total amount of stress applied and the space closure.

Conclusion

A new spring applying a constant and continuous force was designed and compared with a conventional force system.

The results of this study show that:

1. Full space closure with the DS retractor was successful without any reactivation.
2. The continuous and constant force applied by the DS retractor provided more rapid canine movement than the continuous but diminishing force produced by the PC-type spring retractor.
3. The total tooth movement seems to be related

to the cumulative amount of stress generated in the periodontal ligament.

4. Canine retraction occurred faster in adolescents than in adults.

Therefore the DS retractor can be used to determine optimal force levels for different types of teeth and for tooth movement.

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Acknowledgements

This work was based on the MS thesis of the first author, at the University of Gazi, Ankara, Turkey.

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